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# **Progress on Coal-Derived Fuels for Aviation Systems**

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## SUMMARY

The results of engineering studies of coal-derived aviation fuels and their potential application to the air transportation system are presented. Synthetic aviation kerosene (SYN. JET-A), liquid methane ( $\text{LCH}_4$ ), and liquid hydrogen ( $\text{LH}_2$ ) appear to be the most promising coal-derived fuels. Aircraft configurations fueled with  $\text{LH}_2$ , their fuel systems, and their ground requirements at the airport have been identified. These  $\text{LH}_2$ -fueled aircraft appear viable, particularly for long-haul use, where aircraft fueled with coal-derived  $\text{LH}_2$  would consume 9 percent less coal resources than would aircraft fueled with coal-derived SYN. JET-A. Distribution of hydrogen from the point of manufacture to airports may pose problems. Synthetic JET-A would appear to cause fewer concerns to the air transportation industry. The ticket price associated with coal-derived  $\text{LH}_2$ -fueled aircraft appears competitive with that of aircraft fueled with coal-derived SYN. JET-A. Of the three candidate fuels,  $\text{LCH}_4$  is the most energy efficient to produce, and an aircraft fueled with coal-derived  $\text{LCH}_4$  may provide both the most efficient utilization of coal resources and the least expensive ticket as well. The safety aspects associated with the use of cryogenic fuels such as  $\text{LCH}_4$  and  $\text{LH}_2$  in the air transportation system are yet to be determined.

## INTRODUCTION

This paper addresses the use of alternate fuels in the air transportation system and relates the use of such fuels to concerns of the general public, the air transportation industry, and the air traveler. The bulk of the material presented herein is the product of a program sponsored by the NASA Langley Research Center. The program is directed at providing answers to some of the many technical questions which decision makers will face when deciding which alternate fuels will be most advantageous to use and which sectors of the nation's energy consumers should use them.

## ABBREVIATIONS AND SYMBOLS

APU	auxiliary power unit
DCF	discounted cash flow
DOC	direct operating cost
$\text{GH}_2$	gaseous hydrogen
IOC	indirect operating cost

LCH <sub>4</sub>	liquid methane
LH <sub>2</sub>	liquid hydrogen
L/D	lift-drag ratio
M	Mach number
MISC.	miscellaneous
OEM	operating empty mass
PL	payload
SYN. JET-A	synthetic aviation kerosene

#### PUBLIC CONCERNS

Although civil air transportation accounts for only 2 percent of the total United States energy consumption and about 4 percent of the petroleum energy consumed, the utilization of alternate fuels in the air transportation system would affect the general public to varying extents, depending upon the alternate fuel selected. The areas of national needs, candidate fuel selection, and community impact are addressed.

#### National Needs

Oil provides 47 percent of the total energy consumed by the United States (ref. 1) and transportation requires 54 percent of this oil consumption. Figure 1 shows the historical and projected production and consumption of oil in the United States. The projection of domestic oil production was taken from the ERDA document of reference 2. The projected oil consumption represents a relatively modest 2 percent per annum growth rate when compared with the 3.7 percent growth rate which has occurred over the past decade. The United States currently imports about 46 percent of its oil, compared with 41 percent 1 year ago. These imports require an expenditure of \$30 billion per year. The potential role which synthetic fuels, produced from oil shale and coal, might play in filling this gap is shown in figure 2. Figure 2, taken from the Project Independence Report (ref. 3), shows the projected decline of domestic oil and natural gas production after 1985 and the projected demand based on a growth rate of 2.5 percent per annum. The demand model assumed that oil and natural gas would not be used for electricity generation after 1985. As shown in the figure, the report also indicated that a major portion of the gap might be filled by rapid development of synthetic fuels from coal and oil shale.

Thus, a national need for synthetic fuels exists at the present time. However, for reasons which are beyond the scope of this paper, the United States has only an embryonic synthetic fuels industry.



### What Fuels?

There are a number of synthetic fuels which can be produced from United States energy resources. This paper deals only with those which appear suitable for application to aviation. A number of synthetic fuels were judged not to be viable for aviation use and are listed in figure 3 together with their masses and volumes (for equal energy content) relative to JET-A fuel (conventional aviation kerosene) and with the criteria for rejection. JET-A is presented only as a reference. All the synthetic fuels listed in figure 3 were rejected basically because of their higher masses, although toxicity and corrosion were also contributing factors. For a long-range airplane, fuel mass can be 40 to 50 percent of the airplane gross take-off mass. Doubling the mass of the fuel has an adverse domino effect by increasing structural weight and decreasing aircraft performance.

The candidate synthetic fuels judged viable for aviation use are listed in figure 4, where their mass and volume characteristics are compared with those of JET-A fuel. Liquid methane and liquid hydrogen are, of course, cryogenic fuels and must be stored at temperatures of  $-162^{\circ}\text{C}$  and  $-253^{\circ}\text{C}$ , respectively. Both  $\text{LCH}_4$  and  $\text{LH}_2$  have higher relative volumes than JET-A but, more importantly, have lower relative masses. Consideration must also be given to the energy resources (other than conventional oil and natural gas) from which they can be produced. These are as listed in the following table:

Synthetic fuel	Energy source for fuel	Program study area
SYN. JET-A	Coal Oil shale	Fuel production from coal ✓ Aircraft ✓ Air terminal requirements ✓
Liquid methane ( $\text{LCH}_4$ )	Coal	Aircraft and fuel systems Air terminal requirements Fuel production from coal ✓
Liquid hydrogen ( $\text{LH}_2$ )	Coal Nuclear Thermal Organic	Aircraft and fuel systems ✓ Air terminal requirements ✓ Fuel production from coal ✓

The scope of the alternate fuels program being sponsored by the Langley Research Center is also given in the table on the previous page. Synthetic JET-A (SYN. JET-A), liquid methane ( $\text{LCH}_4$ ), and liquid hydrogen ( $\text{LH}_2$ ) are being studied in the program. The study areas for the three fuels include the aircraft and the aircraft fuel systems, ground requirements at the air terminal and airport, and fuel production. The check marks indicate studies which have been completed. Most of the Langley-sponsored effort has been in the areas of liquid hydrogen fuel and the production of all three fuels. Fuel production studies were included in the program in order to obtain a better overall picture of the synthetic fuels options. Fuel production study results are discussed first, since they are most germane to the area of public concerns. Aircraft and airport study results are discussed in later sections.

The Langley-sponsored fuel production studies have been limited to production from coal. Coal was selected as the energy source for the studies because it is the largest fossil fuel resource in the United States (ref. 2) and because all three candidate fuels can be produced from coal, thus providing a common basis for comparison.

Although there are many variations to the many methods for producing fuels from coal, all the processes have one basically common ingredient (fig. 5), which is the production of a synthesis gas. In these processes, coal, steam, and either air or oxygen are combined in a coal gasification vessel to produce a synthesis gas (a gas rich in  $\text{CO}$ ,  $\text{H}_2$ , and  $\text{CH}_4$ ). Part of the coal is reacted with the air or oxygen to provide the heat for the production of the synthesis gas. The constituency of this synthesis gas can be controlled to a great extent by varying the pressure and temperature in the basic coal gasification vessel (ref. 4). What happens to the synthesis gas after it leaves the coal gasifier depends upon the desired end product.

If the end product is to be hydrogen, the synthesis gas production is tailored (high temperature) to produce a gas rich in  $\text{H}_2$ . The  $\text{CO}$  is combined with steam, over the proper catalyst, to produce more  $\text{H}_2$  (labeled as the water-gas shift process in fig. 5).

If the end product is to be methane, the synthesis gas production is tailored (high pressure) to produce a gas rich in  $\text{CH}_4$ . Proper amounts of  $\text{CO}$  and  $\text{H}_2$  are produced to provide for the methanation reaction (a reaction of  $\text{CO}$  and  $\text{H}_2$  over a catalyst), which produces  $\text{CH}_4$ .

If the desired end product is to be SYN. JET-A, there are two basic processes which may be employed. One process is that of coal liquefaction, in which the basic role of the synthesis gas is to provide  $\text{H}_2$ , which is added to the coal to produce a mixture of gases and liquids. There are a number of methods by which the hydrogen can be added to the coal, and the method of hydrogen addition is the major feature which distinguishes one coal liquefaction process from another. (See ref. 5 for details.) The second basic process is known by the generic term as the Fischer-Tropsch process. This process was utilized by Germany in World War II to produce gasoline from coal and is currently being used in South Africa for the production of a variety of fuels

from coal. In the Fischer-Tropsch process, the synthesis gas is reacted over the proper catalyst to produce a mixture of gases and liquids. The proper selection of the catalysts, reaction pressure, and reaction temperature can control the nature of the gases and liquids produced. Portions of the gas product (basically  $H_2$ ) from the coal liquefaction and Fischer-Tropsch processes are utilized to upgrade the liquid products to SYN. JET-A and other liquid fuels.

The processes just described are but general descriptions of how the three fuels may be produced from coal. There are many modifications of these processes, which are more exotic and are aimed at reducing coal consumption, decreasing oxygen requirements, and decreasing production cost. Some of these processes are described in reference 5.

The principal findings of the Langley-sponsored fuel study for three key factors are summarized as follows:

	<u>SYN. JET-A</u>	<u><math>LCH_4</math></u>	<u><math>LH_2</math></u>
Efficiency, coal to fuel, percent . . .	54	64	49
Price for 127 MJ, the energy in 3.79 l (1 gal) of JET-A, cents . . .	67	51	82
Other potential product uses . . . . .	Diesel fuel	Substitute natural gas	Production of chemicals and food

The first factor is the efficiency with which the fuels may be produced from coal. This factor is important from the standpoint of efficient utilization of the remaining United States coal resources and from the cost standpoint as well, since coal cost can be a large contributor to coal-derived fuel costs. Herein, efficiency is defined as the ratio of the heating value of the fuels produced by a process to the heating value of the coal required to produce the fuels. Liquid methane was determined to be the most thermally efficient fuel producible from coal, followed by SYN. JET-A and  $LH_2$ . Also shown is the price of 127 MJ of energy (the energy content of 3.79 l (1 gal) of JET-A fuel) for each fuel. The prices are based on a coal cost of \$22/tonne (\$20/ton) and 1974 dollars. A private-investor financing method was used to determine the return on investment. The basic features of this method are summarized as follows:

Project life	25 years
Depreciation	16-year sum of the digits on total plant investment
Capital	100 percent equity

DCF return rate	12 percent
Federal income tax	48 percent
Return on investment during construction	DCF return rate $\times$ 1.878* years $\times$ Total plant investment
Plant stream factor	90 percent

\* 10 percent for 3 years, 90 percent for 1.75 years.

Liquid methane was determined to be the least expensive fuel, followed by SYN. JET-A and  $\text{LH}_2$ . It was also determined (ref. 5) that because of the higher efficiency associated with the production of  $\text{LCH}_4$ , the price of  $\text{LCH}_4$  was the least sensitive to increases in the cost of the coal used in its production.

The table on the previous page also lists other potential product uses for each fuel. When synthetic fuel plants are built, there will be competition for their outputs from sectors other than air transportation. For instance, there will be competition for synthetic diesel fuel, a distillation fraction similar to SYN. JET-A. There will also be competition for methane for use as substitute natural gas and competition for hydrogen for production of chemicals (such as fertilizer) and for food processing. Reference 6 documents the potential future demand for hydrogen for a variety of uses.

#### Community Impact

Consideration must be given to potential concerns of the community at large which the implementation of the candidate alternate fuels might create. The following table summarizes how two of these concerns - the distribution system and its safety and aircraft emissions - differ, depending upon the fuel selected:

Community concern	SYN. JET-A	$\text{CH}_4$	$\text{H}_2$
Distribution system and safety	No change (JET-A lines)	No change (natural gas lines)	High pressure or large lines
Aircraft emissions (relative to JET-A)	Same or worse	Improved	Greatly improved

Fuel distribution.- It is likely that the plants which will produce coal-derived synthetic fuels will be located where the coal is located. The locations of the major coal deposits in the United States are shown in figure 6. The fuels, once they have been produced, must then be transported to the points at which they will be used - the nation's airports. Figure 7 shows the



existing major liquid petroleum pipeline network as well as the coal deposits in the United States. This extensive existing network could be used to transport coal-derived synthetic JET-A to its ultimate point of use. Figure 8 shows the existing major natural gas pipeline network as well as the coal deposits. These lines could be used to distribute coal-derived methane across the nation, since natural gas is more than 90 percent methane. No such national pipeline network exists for carrying hydrogen.

For equal volumes of gas, the heating value of hydrogen is about 1/3 that of natural gas. Reference 7 has indicated that for fully turbulent pipeline flow and the same pipeline diameter and pressure, the velocity of hydrogen flow in the line is nearly 3 times that of natural gas. Therefore, the major gas lines leading from gas wells, which are generally fully turbulent, could deliver about 90 percent as much energy throughput for hydrogen as for natural gas.

Reference 7 also indicated that although the volume of leakage through cracks and holes would be about 2-1/2 to 3 times greater for hydrogen than for natural gas, the lower energy density of hydrogen (again 1/3 that of natural gas) may more than compensate for its higher leak rate and thus the energy loss would be about the same.

The entire question of the compatibility of natural gas pipelines with hydrogen is being addressed at the present time in experiments sponsored by the U.S. Department of Energy and the gas industry. At the Institute of Gas Technology (IGT) in Chicago, three closed pipeline loops have been assembled to circulate hydrogen gas through natural gas lines, valves, and pumps, which have been donated by the gas industry. The goals of the work at IGT are to determine the energy throughput, pumping requirements, leak rates, and safety aspects associated with the use of the natural gas pipeline system for gaseous hydrogen transportation. Work is underway at the Sandia Laboratories, Livermore, California, to determine the potential problems and solutions associated with hydrogen embrittlement of natural gas pipeline materials. Results of these studies will go far in establishing whether new pipelines will be required for gaseous hydrogen transportation and, if so, how they should be designed and operated to provide safety to the public equal to at least that which exists for natural gas pipelines. Should new pipelines be required for hydrogen transportation, the communities in the path of these pipelines would be disrupted by their installation.

Aircraft emissions.— The emissions characteristics of the alternate fuels relative to JET-A fuel are summarized in a previous table. When SYN. JET-A is referred to in this paper, it is assumed that the quality and physical characteristics of the fuel are the same as current-day JET-A specifications. There are, however, trade-offs which might be made between fuel specifications, fuel costs, and efficiency of production. Synthetic JET-A of lesser quality could be produced at a somewhat lower cost and at a greater efficiency, but the emissions from an aircraft utilizing the fuel would increase as would engine maintenance. The problem is basically that of increasing or decreasing the hydrogen content of the fuel. The higher the hydrogen content of the fuel, the better the emissions characteristics and engine maintenance requirements. Adding hydrogen to the fuel costs money and energy, however.

Use of either  $\text{LCH}_4$  or  $\text{LH}_2$  compared with SYN. JET-A should result in improved emissions characteristics. Hydrogen is considered to be an environmentally superior fuel, its only combustion products being water and oxides of nitrogen. Lean burning (ref. 5) offers the potential for drastic reduction of oxides of nitrogen.

#### INDUSTRY CONCERNS

The introduction of alternate fuels into the air transportation system will have a maximum impact on the air transportation industry. Industry concerns are addressed in this section from the standpoint of the air transport manufacturers, the operational aspects, and the airport itself.

#### Air Transport Manufacturers' Concerns

The following table summarizes how synthetic fuel selection may cause concerns to the engine and airframe manufacturers, if and when such fuels are utilized:

System	SYN. JET-A	$\text{LCH}_4$	$\text{LH}_2$
Engines	Present aircraft compatible	Present engines compatible but R & D could improve efficiencies over JET-A	
Aircraft fuel system		Presently unidentified, work underway	System identified R & D needs Cryoinsulation Pumps
Aircraft configuration			Defined Best with fuselage tanks Certification?

Synthetic JET-A would (again if the fuel specifications are unchanged) be completely compatible with the present aircraft and their systems. A study of the characteristics of methane-fueled aircraft has just been initiated by Langley with the Lockheed-California Company (CaLAC), and the results of this study should help to define what demands  $\text{LCH}_4$  would place upon the air transport manufacturers.

Considerable information has been obtained on the characteristics of aircraft fueled with liquid hydrogen. The study of reference 8 was carried on in 1974 by the Lockheed-California Company (CaLAC) to determine how an  $\text{LH}_2$ -fueled aircraft should be configured, where the fuel should be stored onboard the aircraft, and how well the aircraft would perform in relation to aircraft

fueled with JET-A. The results of this study are summarized in figure 9 for subsonic aircraft designed to carry 400 passengers 10 000 km. The empty masses of the two aircraft were about the same. The big difference was in the mass of the fuel required by the Jet-A aircraft, which amounted to about 3 times that required by the LH<sub>2</sub> aircraft. This difference resulted in a gross take-off mass 25 percent lower and a wing area 20 percent less for the LH<sub>2</sub> aircraft, as shown in the plan view to the left of the figure. The smaller wing of the LH<sub>2</sub> aircraft, combined with an 11 percent longer and 13 percent wider fuselage, resulted in a cruise lift-drag ratio of 16, compared with 18 for the JET-A aircraft; but this decrease in aerodynamic efficiency was overridden by the lower gross take-off mass of the LH<sub>2</sub> aircraft. The energy consumption (on-board energy only, exclusive of fuel production energy) was 10 percent less for the LH<sub>2</sub> aircraft than for the JET-A aircraft (706 kJ/seat-km for LH<sub>2</sub> versus 786 kJ/seat-km for JET-A).

The initial CaLAC study (ref. 8) also determined that the best place to locate the low-density LH<sub>2</sub> fuel was in tanks within the fuselage, both fore and aft of the double-decker passenger compartment, as shown in the illustration of figure 10. External wing tank configurations were also studied, but the drag caused by the tanks resulted in excessive fuel consumption. The major difference identified (but not detailed) between an LH<sub>2</sub> aircraft and one fueled with conventional JET-A would be in the fuel systems.<sup>2</sup> A follow-on effort by CaLAC (under Contract NAS1-14614) is nearly completed and addresses the conceptual design of the total fuel system of an LH<sub>2</sub> aircraft, optimized for total fuel system and aircraft performance. The study considers all aspects of the fuel system, (e.g., fuel containment, fuel delivery, fuel flow control, and engine), as illustrated in figure 11. Identified highlights of the study, summarized in figure 12, include the design of a workable, light-weight, integrated fuel system; an 18-percent onboard energy savings for the LH<sub>2</sub> aircraft over JET-A aircraft (compared with 10 percent identified in the earlier 1974 effort); and a 9-percent savings in coal resources, compared with the coal resources required to power SYN. JET-A aircraft. The coal resources considered include the energy content of the coal required to produce the synthetic fuels.

The study also pointed out that the performance (based on the thrust per megajoule of fuel) of engines designed to use LH<sub>2</sub> may be superior to that of engines fueled with JET-A (about 5 percent, which contributes to the 18-percent onboard energy savings). Research and development effort was identified as needed in this area as well as in the areas of insulation and pumps.

The certification of an LH<sub>2</sub> aircraft and its fuel system was only partially addressed in the study and remains a moot question. Testing will be required to provide the development of new components, the qualification of components and subsystems, and the demonstrations of complete systems performance, safety, and reliability prior to flight testing. In carrying out the design study of the LH<sub>2</sub> aircraft fuel system, consideration was given to the Federal Airworthiness Regulations. For instance, each of the two fuel tanks was subdivided into two tanks in order to provide compliance with Section 953 of FAR 36 (ref. 9), which requires an independent fuel supply system for each engine. The study

also identified portions of the Federal Airworthiness Regulations which had been developed specifically for JET-A fuel but which would not be directly applicable to LH<sub>2</sub> aircraft. Specific revisions to the regulations, consistent with the intent of the regulations but tailored specifically for LH<sub>2</sub>, were also defined.

#### Operational Concerns

Use of synthetic fuels will have varying effects on the operational aspects of the air transportation system, as shown in the following table:

Operational aspect	SYN. JET-A	LCH <sub>4</sub>	LH <sub>2</sub>
Aircraft size*	Present aircraft compatible	Presently undefined	More viable for large aircraft and long haul
Introduction to fleet*		Phase-in problems: All new aircraft Fuel availability	
Engine maintenance*		20 to 30% less (2.5% less DOC)	
Turnaround time*		Presently undefined	Compatible
Safety*		?	?

\*Relative to JET-A.

SYN. JET-A is seen to be compatible with present aircraft in all operational aspects. With regard to the cryogenic fuels, a point-design long-haul LCH<sub>4</sub> aircraft is currently under study by CaLAC, as mentioned previously. Turn-around times for the LCH<sub>4</sub> aircraft are to be determined in the study, but the performance of LCH<sub>4</sub> aircraft sized for different range-payload missions will not be addressed. The performance of LCH<sub>4</sub> aircraft should not be as sensitive to changes in design mission as is the performance of LH<sub>2</sub> aircraft, since LCH<sub>4</sub> requires 60 percent more fuel volume than JET-A, compared with 300 percent more fuel volume required for LH<sub>2</sub>. The CaLAC LH<sub>2</sub> aircraft studies (refs. 8 and 10), which addressed a number of range-payload combinations, determined that LH<sub>2</sub> aircraft were more viable for large aircraft and long-haul missions, both of which require use of a large amount of energy.



The introduction of cryogenic fuels to the fleet may cause phase-in problems. New aircraft designed specifically for cryogenic fuels will certainly be required for LH<sub>2</sub> and most probably for LCH<sub>4</sub> as well. Fuel availability, both nationwide and worldwide, could also be a problem with cryogenic fuels.

Regarding engine maintenance, the CaLAC LH<sub>2</sub> fuel system study determined that from experience obtained by pumping natural gas and utilizing natural gas as a pump fuel (essentially CH<sub>4</sub>), 20 percent less maintenance can be expected from turbine engines burning methane. On the basis of these data, expected engine maintenance is estimated to be 30 percent less from the use of hydrogen. This lower engine maintenance translates into a 2.5-percent decrease in direct operating cost for LH<sub>2</sub> aircraft.

Turnaround times for LCH<sub>4</sub> aircraft are presently undefined but are to be determined in the CaLAC LCH<sub>4</sub> study. The studies of references 11 and 12, which analyzed the ground requirements for LH<sub>2</sub> aircraft at the airport, determined that LH<sub>2</sub> aircraft fueling, servicing, and passenger movements could be accomplished within conventional turnaround times.

The safety aspects associated with the use of either LCH<sub>4</sub> or LH<sub>2</sub> as an aircraft fuel have not been determined. However, safety was a prime consideration in the studies of LH<sub>2</sub> aircraft and their ground requirements at the airport.

In the CaLAC LH<sub>2</sub> aircraft fuel system study, the design of the system included failure mode analyses. For instance, in screening the various fuel tank insulation concepts, a design criterion was that no single or probable combination of failures would lead to loss of life or aircraft.

#### Airport Concerns

The introduction of synthetic fuels into the air transportation system may cause new concerns regarding operations at the airport. Some of these concerns are listed in the following table:

Airport concern	SYN. JET-A	LCH <sub>4</sub>	LH <sub>2</sub>
Fuel supply	Present systems compatible	Proximity to natural gas distribution	Proximity to H <sub>2</sub> manufacturer <sup>2</sup>
Fuel processing and storage		On-site liquefaction and storage land area generally available	
Fuel delivery to aircraft		Presently undefined, work underway	Safe system defined
Aircraft maintenance area			New facilities required
Passenger enplanement			Double-deck aircraft accommodations

With SYN. JET-A, all systems and operations will be compatible with those presently in use. With methane, the proximity of the fuel supply would be as close as the nearest natural gas pipeline. Whether or not the existing natural gas pipelines could be used for the transport of gaseous hydrogen is a moot question. As discussed in the section entitled "Fuel Distribution," tests are currently being conducted to determine the compatibility between natural gas lines and gaseous hydrogen. Should new lines be required for hydrogen, the proximity of the airport to the  $H_2$  manufacturer may be a concern.

The ground requirements for  $LCH_4$  aircraft at the airport are presently undefined but are being addressed in the CaLAC  $LCH_4$  study which is currently underway.

Dual studies of the requirements for hydrogen-fueled aircraft at the airport were conducted by Boeing (ref. 11) and CaLAC (ref. 12). The studies assumed that all wide-body jets at two major airports (Chicago-O'Hare International Airport and San Francisco International Airport) would be fueled with  $LH_2$ . It was determined that sufficient land area was available at both airports for the required on-site hydrogen liquefaction and storage facilities. Although methane liquefaction and  $LCH_4$  storage facilities were not addressed in these studies, it appears reasonable that sufficient land area would exist for methane liquefaction and storage facilities, since methane liquefaction is less complex than hydrogen liquefaction and  $LCH_4$  requires less storage volume than  $LH_2$ . Closed-loop systems were defined for delivering the  $LH_2$  from storage to the aircraft. It was also determined that to prevent accumulation of hydrogen vapors in aircraft maintenance buildings, new defueling and maintenance facilities would be required for  $LH_2$  aircraft. The earlier  $LH_2$  aircraft configuration studies determined that the  $LH_2$  fuel should be stored in large-diameter tanks fore and aft of a double-deck passenger compartment. Therefore, for ease of passenger emplanement, double-deck passenger loading facilities at the air terminal would be required.

A schematic view of the  $LH_2$  fuel facilities at the airport is shown in figure 13. Gaseous hydrogen is delivered to the airport via pipeline and thence to a liquefaction plant, where the hydrogen is liquefied and stored in large cryogenic vessels. The  $LH_2$  is pumped through two pipelines (vacuum jacketed) and is continuously circulated around the perimeter of the air terminal and returned to the storage vessels. Two  $LH_2$  lines are utilized to provide system redundancy. Despite the fact that the  $LH_2$  fuel tanks on-board the aircraft will never be completely empty during normal use, the temperature of a large portion of the tank will be significantly higher than that of the  $LH_2$ . About 15 percent of the  $LH_2$  placed in the aircraft will be vaporized as a result of  $H_2$  vapors created during tank cool down, resaturation of the  $LH_2$  in the aircraft fuel tank, boil-off prior to fueling, and displaced ullage gas. The studies showed that it is desirable from the standpoints of cost and energy conservation to collect the cold  $H_2$  vapors and reliquefy them. To this end, the third pipeline shown in figure 13 is used to capture the  $H_2$  vapors and return them to the liquefaction plant for reliquefaction. Hydrogen vapor created by boil-off in the storage vessels and by the flashing of the  $LH_2$  returning to the storage vessels is also reliquefied. The  $LH_2$  distribution lines and  $H_2$  vapor collection lines are located in either open trenches with

steel grates covering the trenches or are buried in positively ventilated tunnels. Tunnels could be made under the runways without interrupting airport operations.

Figure 14 illustrates in more detail the process at each hydrant whereby the aircraft are fueled. Each airline is provided with an appropriate number of fueling hydrants. A hydrant truck is used to connect the hydrant to the aircraft. Two lines are connected to the aircraft, one for delivering the  $LH_2$  fuel to the aircraft and one for returning the cold  $H_2$  vapors produced during aircraft fueling to the liquefaction plant for subsequent reliquefaction. After the aircraft has been fueled, the line which connects the hydrant to the aircraft is purged with helium (carried in pressurized bottles on the truck), and the mixture of helium and hydrogen is transferred via a small third line to the return vapor line to the liquefaction plant. This process permits the recovery of the  $H_2$  in the line and, more importantly, the recovery of the purge helium.

The ground systems defined by Boeing and CalAC are completely enclosed and permit essentially no  $H_2$  to escape. Estimates of the capital investments required to provide  $LH_2$  facilities at Chicago-O'Hare International Airport and San Francisco International Airport were \$469 million and \$340 million, respectively. In an earlier section of this paper ("What Fuels?") the price of coal-derived alternate fuels was discussed. The fuel prices shown for  $LCH_4$  and  $LH_2$  include the amortized capital investment required for liquefaction plants. The hydrogen liquefaction plants represent a major portion (60 to 85 percent) of the capital investment required for the  $LH_2$  airport facilities.

Although safety was a prime consideration in the  $LH_2$  airport studies, the safety aspects associated with the use of  $LH_2$  and  $LCH_4$  at the airport are yet to be fully determined. Overall, SYN. JET-A would appear to cause fewer concerns to the air transportation industry than would either  $LCH_4$  or  $LH_2$ .

#### AIR TRAVELER'S CONCERNS

Three major concerns to the air traveler are safety, service, and cost. Synthetic JET-A would effect no change to safety and service. The safety aspects, as they concern the air traveler, have not been determined for  $LCH_4$  or  $LH_2$ . However, if a fuel release occurs during an aircraft crash, the more volatile the fuel, the greater the likelihood of a fire. Liquid methane and liquid hydrogen are more volatile than SYN. JET-A. In addition, the minimum energy for ignition of  $H_2$  in air is 1/10 that of  $CH_4$  and SYN. JET-A; thus an even greater possibility of fuel ignition exists for  $H_2$ . However, mitigating factors may be the characteristics of an  $H_2$  fire - mainly its short duration and lower thermal radiation and the fact that no asphyxiating smoke occurs.

With regard to service and delays, the Boeing and CalAC  $LH_2$  airport studies indicated that the use of  $LH_2$  should not cause ground delays and that the required modifications to the airport should not cause an interruption in services. As mentioned previously, an insufficient nationwide and worldwide availability of  $LCH_4$  or  $LH_2$  could introduce inconveniences to the air traveler,

particularly during the early phases of implementation of such fuels. Obviously, the aircraft using these fuels could fly only to and from locations where the fuels were available. Not all countries have coal resources (or oil shale for that matter) from which to produce synthetic fuels. Insight into these potential problems will be obtained as the synthetic fuels industry develops in the United States and abroad.

Regardless of which synthetic fuel is selected, the air traveler will pay a higher price for an airline ticket. The bar graph shown in figure 15 illustrates the passenger ticket price for transport aircraft which utilize synthetic coal-derived aviation fuels, and JET-A fuel at 9.5¢/l (36¢/gal). Each bar is divided to show amounts associated with direct operating cost (DOC), indirect operating cost (IOC), and miscellaneous costs (MISC.). The shaded area of DOC indicates that portion of the ticket price associated with fuel cost. Two ticket prices are shown for the coal-derived fuels, one for which the coal used to produce the fuels costs \$11/tonne (\$10/ton) and one for which the coal costs \$33/tonne (\$30/ton). The ticket cost bar for the LCH<sub>4</sub> is dashed, as it is based on a "best guess" performance of LCH<sub>4</sub> aircraft. More definitive performance figures will be obtained from studies by CalAC now underway. The synthetic fuel costs do not include the costs associated with storing and distributing the fuels at the airport. The major portion of the LH<sub>2</sub>, and most likely of the LCH<sub>4</sub>, fuel costs is however represented here, since the fuel costs include the liquefaction plant - which (from refs. 11 and 12) is the major airport facility cost for LH<sub>2</sub> (again, 60 to 85 percent). The principal point to be made from figure 15 is that the ticket cost associated with LH<sub>2</sub> is competitive with that of SYN. JET-A if coal costs \$11/tonne (\$10/ton) and is slightly lower if coal costs \$33/tonne (\$30/ton). Liquid methane may provide the least expensive ticket of the three coal-derived fuels. It must be mentioned that the fuel costs shown in figure 15 are based on 1974 dollars. Should the fuel costs be updated to current year dollars, the ticket cost associated with all the synthetic fuels would increase.

#### CONCLUDING REMARKS

The results of engineering studies of coal-derived aviation fuels and their potential application to the air transportation system have been presented. Synthetic aviation kerosene (SYN. JET-A), liquid methane (LCH<sub>4</sub>), and liquid hydrogen (LH<sub>2</sub>) appear to be the most promising coal-derived fuels.

To date, most of the aviation systems studies have centered on LH<sub>2</sub> as a fuel. Liquid-hydrogen-fueled aircraft configurations, their fuel systems, and their ground requirements at the airport have been identified. From these studies, LH<sub>2</sub> aircraft appear viable, particularly for long-haul use, where aircraft fueled with coal-derived LH<sub>2</sub> would consume 9 percent less coal resources than would aircraft fueled with coal-derived SYN. JET-A. Distribution of hydrogen from the point of manufacture to airports may pose problems. Synthetic JET-A would appear to cause fewer concerns to the air transportation industry than would either LCH<sub>4</sub> or LH<sub>2</sub>. The ticket price associated with coal-derived LH<sub>2</sub>-fueled aircraft appears competitive with that of aircraft fueled with coal-derived SYN. JET-A.



Of the three candidate fuels,  $\text{LCH}_4$  is the most energy efficient to produce, and an aircraft fueled with coal-derived  $\text{LCH}_4$  may provide both the most efficient utilization of coal resources and the least expensive ticket as well. Ongoing studies will provide a better assessment of the potential for  $\text{LCH}_4$  as an aircraft fuel.

Although safety was given prime consideration in the systems studies reported, the safety aspects associated with the use of cryogenic fuels, such as  $\text{LCH}_4$  and  $\text{LH}_2$ , in the air transportation system are yet to be determined.

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Hampton, VA 23665  
April 28, 1978

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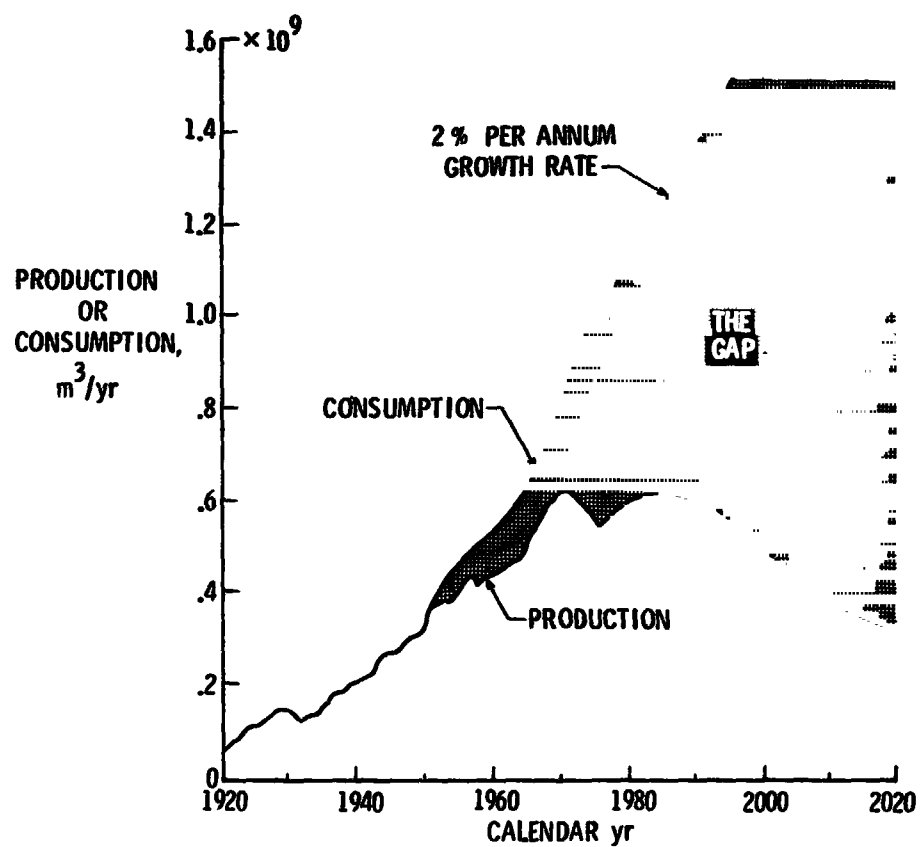


Figure 1.- Historical and projected production and consumption of oil in the United States.

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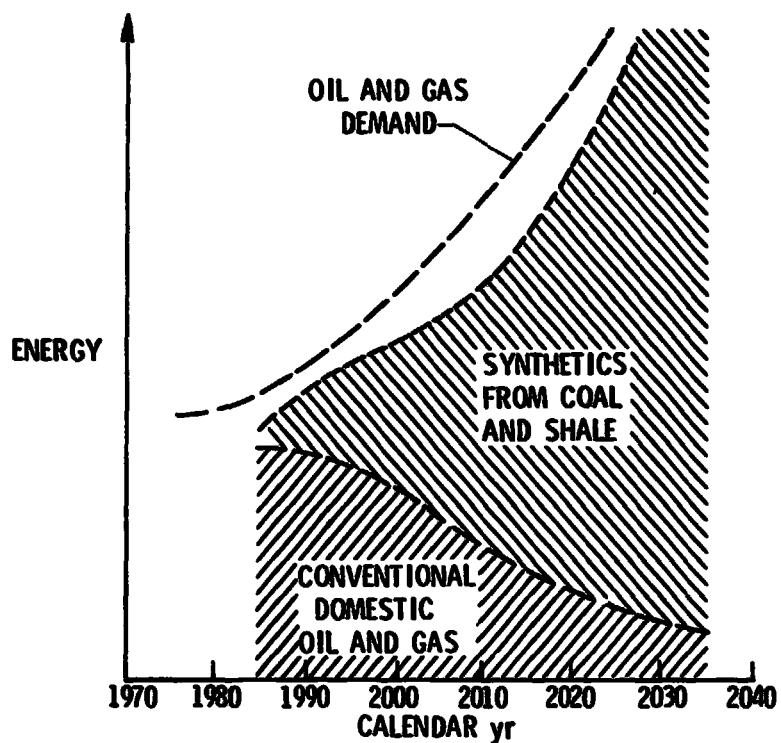


Figure 2.- Potential role of synthetic fuels in the United States, as posed by Project Independence (ref. 3).

	RELATIVE MASS	RELATIVE VOLUME	CRITERIA FOR REJECTION
JET-A (REFERENCE)	1	1	
METHANOL ( $\text{CH}_3\text{OH}$ )	2.18	2.16	MASS
AMMONIA ( $\text{NH}_3$ )	2.30	2.70	MASS, CORROSION, TOXICITY
HYDRAZINE ( $\text{N}_2\text{H}_4$ )	2.56	2.02	MASS, CORROSION, TOXICITY
ETHANOL ( $\text{C}_2\text{H}_5\text{OH}$ )	1.91	1.95	MASS

Figure 3.- Candidate synthetic liquid fuels judged not to be viable for aviation use.











	RELATIVE MASS	RELATIVE VOLUME
JET-A (REFERENCE)	 1	 1
SYN. JET-A	 1	 1
LIQUID METHANE	 0.86	 1.61
LIQUID HYDROGEN	 0.36	 4.02

Figure 4.- Candidate synthetic liquid fuels judged viable for aviation use.

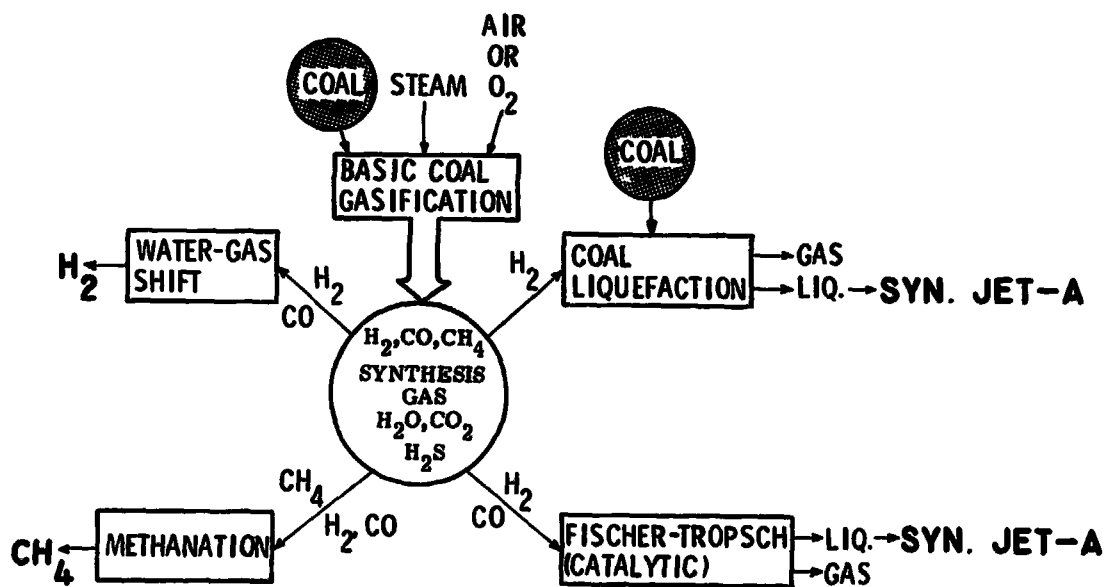


Figure 5.- Production processes for coal-based synthetic fuels.

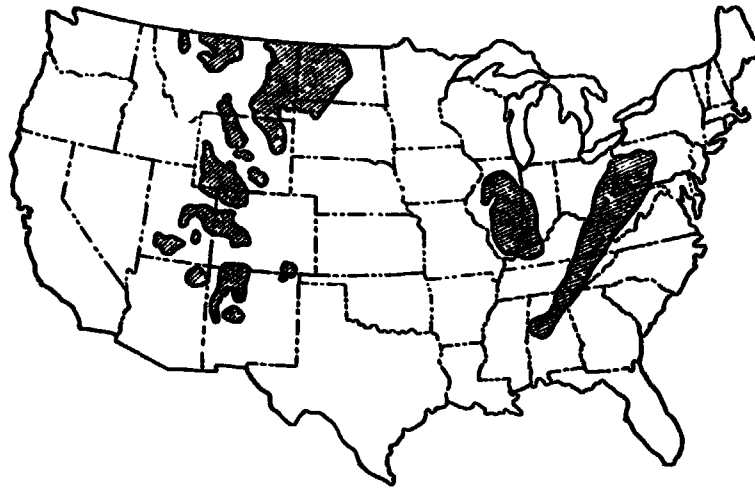
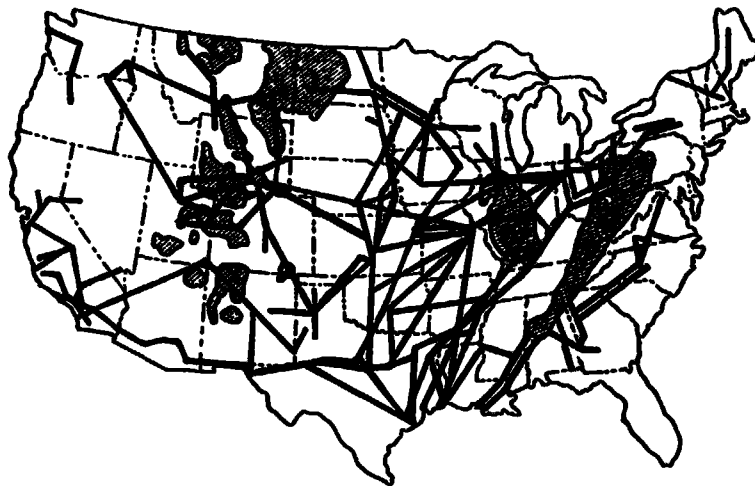
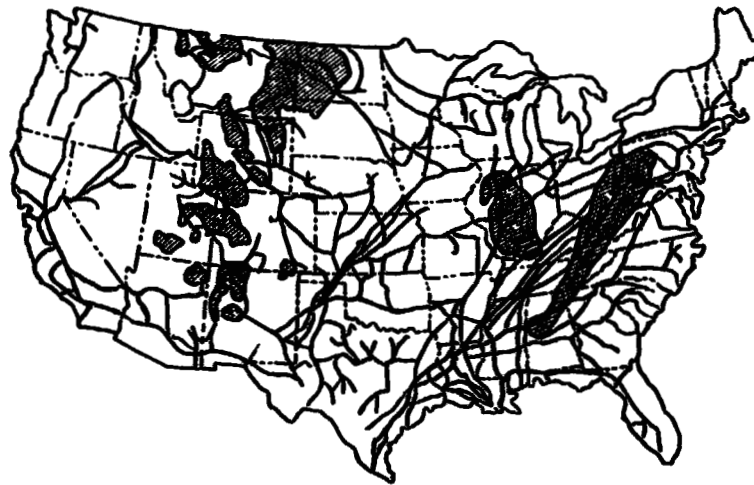


Figure 6.- Locations of major coal deposits in the United States.



— MAJOR LIQUID PETROLEUM PIPELINES

Figure 7.- Locations of major coal deposits in the United States with respect to existing major liquid petroleum pipeline network.



— MAJOR NATURAL GAS LINES

Figure 8.- Locations of major coal deposits in the United States with respect to existing major natural gas pipeline network.

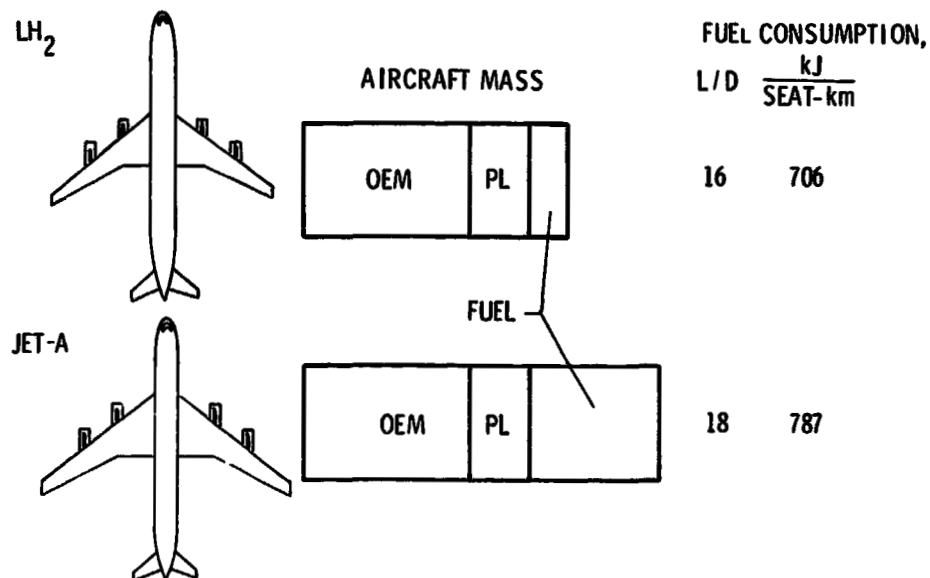


Figure 9.- Comparison of transport aircraft fueled with JET-A and with LH<sub>2</sub>.  
M = 0.85; 400 passengers; range, 10 000 km.

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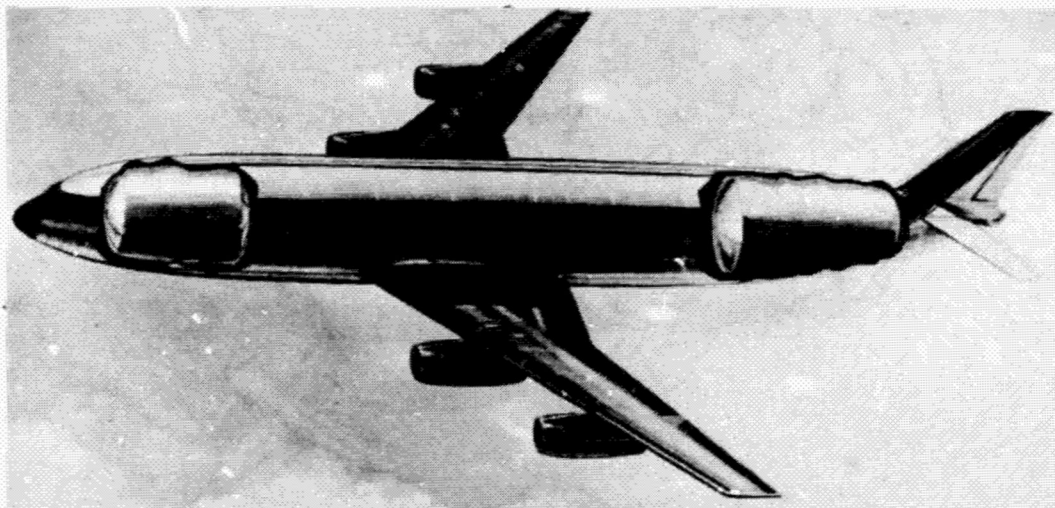


Figure 10.- Cutaway drawing of a subsonic  $\text{LH}_2$ -fueled transport aircraft.

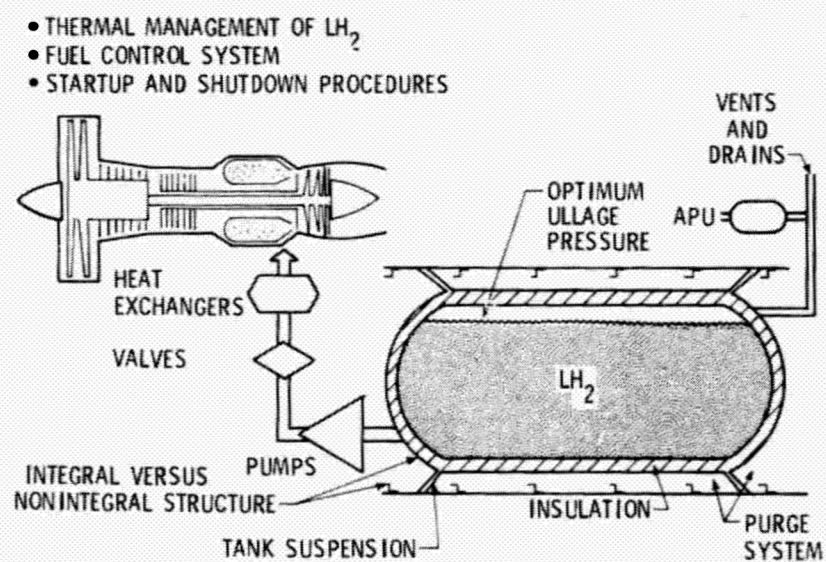


Figure 11.- Aspects considered during conceptual design of the fuel system for an  $\text{LH}_2$ -fueled aircraft.



Figure 12.- Overview and highlights of fuel system study for LH<sub>2</sub>-fueled aircraft.

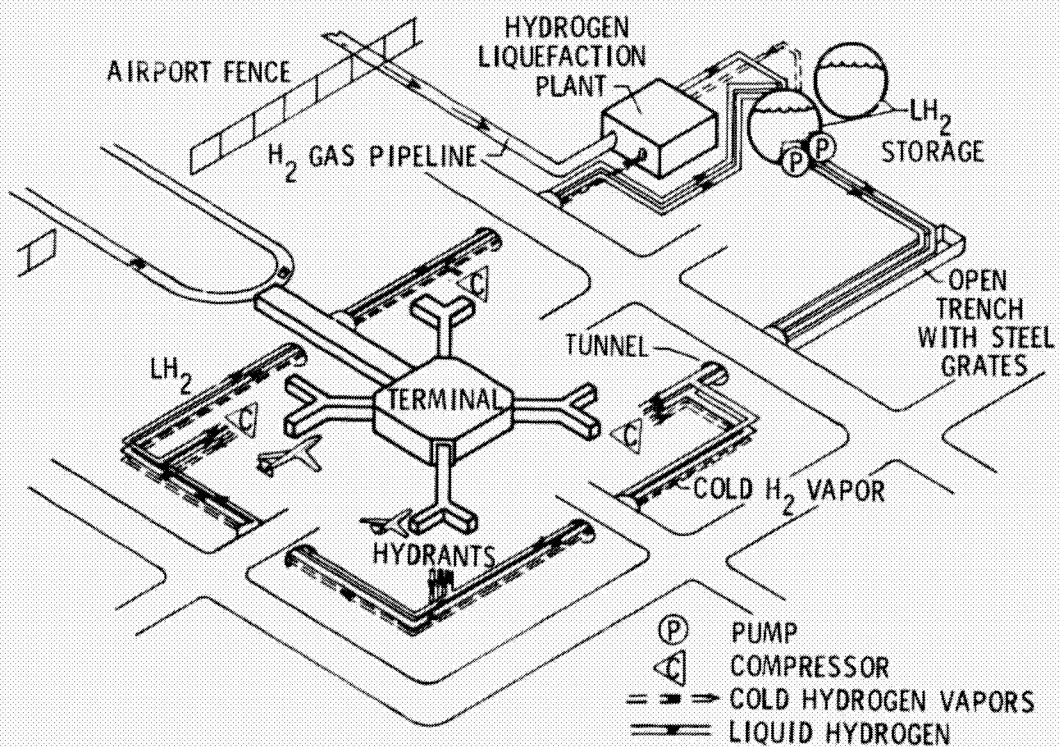


Figure 13.- Schematic of hydrogen liquefaction, storage, and distribution system at an airport.

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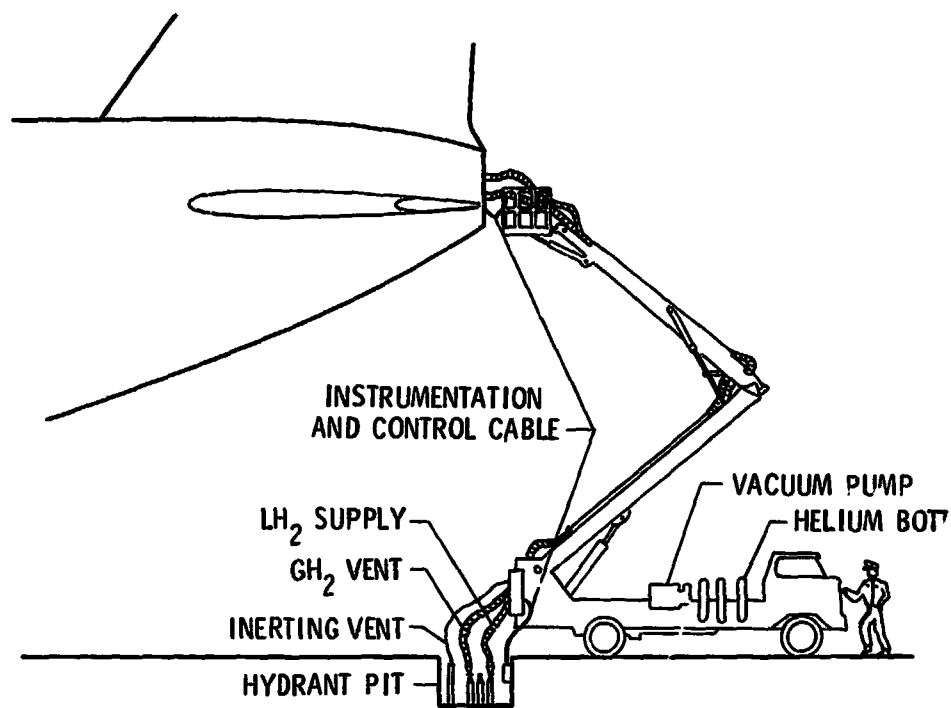


Figure 14.- Fueling of an aircraft with LH<sub>2</sub> via a hydrant truck.

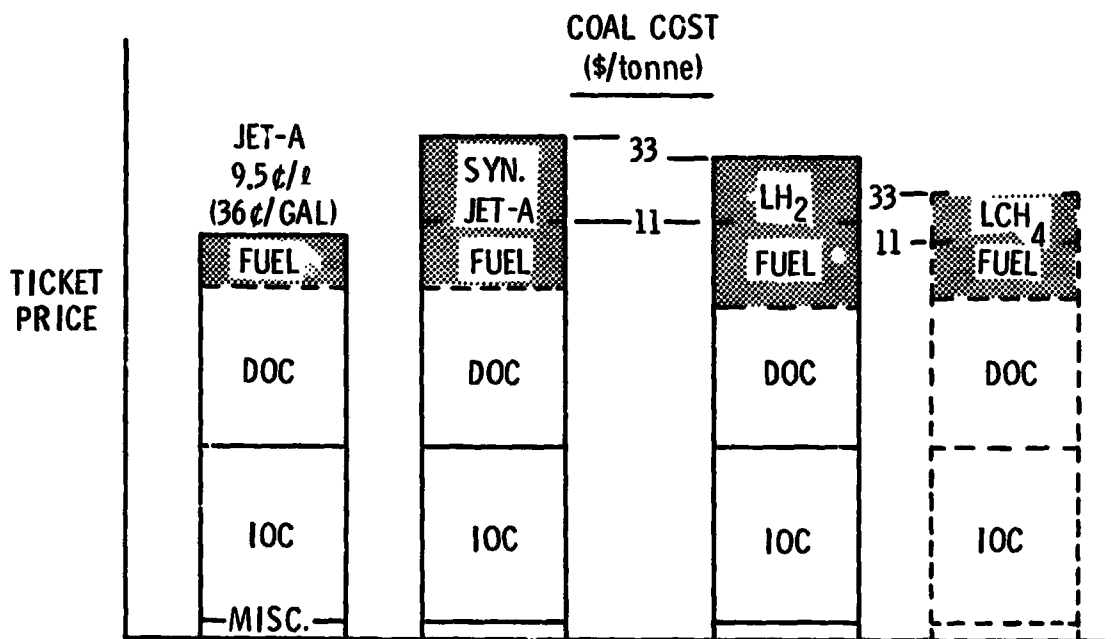


Figure 15.- Effect of coal-derived fuels on airline passenger ticket price, compared with JET-A at 9.5¢/l (36¢/gal) for coal costs of \$33/tonne and \$11/tonne (\$30/ton and \$10/tor).

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